

SYSTEM AND METHOD FOR WIRELESS LOCATION
COVERAGE AND PREDICTION

CROSS-REFERENCE TO RELATED APPLICATIONS

This patent application claims the benefit of the filing date of United States Provisional Patent Application Serial No. 60/202,147, filed May 5, 2000 and entitled "PERFORMANCE ANALYSIS TOOL FOR LOCATION SYSTEMS", the entire contents of which are hereby expressly incorporated by reference.

FIELD OF THE INVENTION

The present invention relates to a system and method for wireless location systems. More specifically, the invention relates to a performance analysis software tool designed to predict the performance and geographical coverage of wireless location systems.

BACKGROUND OF THE INVENTION

Various location determining systems (LDS) are used to determine the location of a mobile user. For example, a Global Positioning System (GPS) typically uses a set of twenty-four orbiting satellites to allow ground-based users to determine their locations. These systems provide the user with location information based on LDS such as GPS data. Some location systems include LDS elements integrated into a cellular phone, while others have equipment added to the wireless infrastructure.

Designing a location system has been cumbersome and involves manipulation and analysis of a variety of information. Location sensor density and geometry are extremely important to obtaining acceptable location data. For example, Angle of Arrival (AOA) techniques require sensor information from a minimum of two sites to obtain a location, three to estimate the quality of a location and a minimum of four to identify and reject severely corrupted (multipath) data from one site. Time

1 Difference of Arrival (TDOA) techniques (both at the sites and
in the handsets) require sensor information from a minimum of
three, four, and five sites for the same capabilities. Factors
5 such as the type of service area to be covered (rural vs. urban)
or the characteristics of the wireless network (existing cell
site densities, geometry of cell sites with respect to each other
and areas to be covered, restrictions on antenna placement,
availability at cell sites, etc.) are all factors affecting
10 location performance and are incorporated in this software
platform.

15 The geometry of the site infrastructure has a major impact
on the quality of the locations. Geometric Dilution Of Precision
(GDOP) plays an important role which must be considered. An
extreme example of poor geometry is found along (relatively)
straight highways between major cities. In these cases, cell
sites are often located in a string near the highways providing
cellular/PCS coverage only to the highway. An AOA location
system with sensors located only at the sites will only be able
20 to locate a mobile set as being between two highway sites. TDOA
systems will only be able to locate the mobile set along a
hyperbola intersecting the highway. This is at least better
information if one can assume that the mobile set is on the
highway and not on a nearby farm-to-market road. Even this would
25 require a unique algorithm for use only in these areas. Note
that a combined AOA/TDOA system would be able to provide location
services under these circumstances.

30 Location systems have coverage requirements that conflict
with those of Cellular/PCS networks. For example, an objective
of a cellular/PCS design is to limit the radio coverage of a
given base station. A location system, on the other hand,
requires that each receiver site "see" (i.e., receive a useful
signal) well beyond the limits of a single base station. A
location system or technique generally operates the best, i.e.,
35 it offers the best accuracy for the highest percentage of the

1 time, when it has an abundance of sites that receive the signal
from the phone. This means that the higher the number of
receiver sites that "see" the mobile unit the better the
5 performance.

As explained above, because of the divergent requirements
of wireless communication and wireless location systems, a
specialized design and analysis software tool is required for
proper design of a location system. There are a number of
10 Cellular/PCS coverage design tools available on the market but
none provide the utility to predict a location system coverage.

Therefore, there is a need for a software tool for analyzing
wireless location systems with a user friendly graphical user
interface (GUI).

15 SUMMARY OF THE INVENTION

The software of the present invention predicts the
availability and accuracy of locations determined by a variety
of different techniques such as Angle of Arrival (AOA), Time of
Arrival (TOA), Time Difference of Arrival (TDOA), and hybrid
20 variations of these angle and time of arrival as well as signal
strength based techniques. The tool is capable of performance
analysis whether the pertinent measurements are performed in
fixed sensors associated with the network infrastructure, or in
the handset. The tool can also determine if the deployed
25 location sensors meet, exceed, or fall short of providing the
expected coverage and performance. The tool allows the location
system designer to eliminate redundancies if not all sensors are
needed and propose additional sites where location coverage holes
are present. The software tool offers similar capabilities to
30 location and monitoring services (LMS) networks.

In one aspect the present invention describes a method for
analyzing performance of a wireless location system. The method
includes the steps of storing data related to location equipment,
35 wireless infrastructure, handsets, terrain map, and morphology

1 map; generating a site radial file for path loss and time/angle
error based on the stored terrain and morphology maps; computing
a multi-site forward and reverse link signal strength map for
5 determining coverage of the location system; generating a multi-
site margin/error map from the computed multi-site forward and
reverse link signal strength map and the stored data; and
generating an error estimate map for the location system.

10 In another aspect, the present invention discloses a system
for performance analysis of a location system comprising: means
for generating a radial model and a radial map including a
plurality of radial paths for a site from a stored raster map;
means for selecting a propagation model from a stored plurality
15 of propagation models for predicting a path loss along each
radial path; at each point along a radial path, means for
predicting accumulated angular errors and time delay errors; and
means for generating an error estimate from the path loss and the
accumulated angular errors and time delay errors.

20 BRIEF DESCRIPTION OF THE DRAWINGS

The objects, advantages and features of this invention will
become more apparent from a consideration of the following
detailed description and the drawings, in which:

25 FIG. 1 is a simplified process flow, according to one
embodiment of the present invention;

FIG. 2 is a simplified process flow related to FIG. 1,
according to one embodiment of the present invention;

FIG. 3 is a picture providing an example screen of a GUI,
according to one embodiment of the present invention;

30 FIG. 4 is an exemplary window within the GUI of FIG. 3;

FIG. 5 is a simplified process flow for generating site
radial maps for terrain and land use, according to one embodiment
of the present invention;

FIG. 6 is a simplified process flow for generating site radial maps for path loss and time/angle error, according to one embodiment of the present invention;

FIG. 7 is a simplified process flow for generating rectangular maps from radial maps, according to one embodiment of the present invention;

FIG. 8 is a simplified process flow for generating a cluster map, according to one embodiment of the present invention;

FIG. 9 is a simplified process flow for generating forward and reverse link signal strengths, according to one embodiment of the present invention;

FIG. 10 is a simplified process flow for generating mobile unit transmit power, according to one embodiment of the present invention;

FIG. 11 is a simplified process flow for generating a multi-site time/angle error map, according to one embodiment of the present invention;

FIG. 12 is a simplified process flow for generating a location error map, according to one embodiment of the present invention;

FIG. 13 is an exemplary picture showing location error in a metropolitan area, according to one embodiment of the present invention;

FIG. 14 is an exemplary picture showing number of location sensors receiving useful signal from a handset, according to one embodiment of the present invention; and

FIG. 15 is an exemplary block diagram of a software tool, according to one embodiment of the present invention.

DETAILED DESCRIPTION

The present invention is a performance analysis software tool designed to predict the performance and geographical coverage of a wide array of wireless location systems. The tool applies to both network-based and handset based location

1 technologies. These location techniques find broad application
in Cellular and PCS networks, as well as in other wireless
networks, including those for LMS. The software tool of the
5 present invention is designed to work as a stand alone package
or as a value added adjunct to wireless communication network
design tools.

10 In one embodiment, the software tool of the present
invention provides a windows based user interface that is fairly
simple to use by a radio or design engineer. It also provides
outputs in the forms of graphs, tables and reports for display
and/or printing. In one embodiment, the tool runs on a Pentium-
based, IBM-PC compatible machine running Windows NT 4.0.
15 However, hosting on other platforms with a variety of different
operating systems such as Linux or UNIX are also provided. The
tool is modular in its structure to allow the gradual inclusion
of capabilities and features, as well as to support on-going
refinements. The typical user does not need to perform any
programming, although hooks are made available to add modules by
20 authorized technical users. Such development could be initiated
based on the users' unique needs and requests.

25 The accuracy of the location determination is described by
the expected location determination error (based on the mean
square error). There are two widely used definitions for
availability, and both capabilities are provided by the tool.
In one, availability is determined by whether location
determination is feasible at all or not. This relates directly
to the minimum number of location sites (sensors) that "cover"
a specific point under consideration on the map. (The minimum
30 number of sites required to yield a location varies from one
technique to another and is described briefly below for the
different techniques.) In the second definition, availability
is whether a location system statistically provides a location
accuracy that meets a pre-selected accuracy threshold for
35 example, 100 m over 67% of a given area.

1 In the family of network or infrastructure based location
techniques, the position determination is performed by means of
sensors that are placed at fixed locations, most typically co-
located with the wireless cell sites.

5 For example, AOA sensors include specially designed antennas
mounted at cell sites or other propitious locations to measure
the angle of arrival of the mobile signal. Because the wave
front arrives at the differently positioned antenna elements at
10 slightly different times, the phase measured at each element
relative to the others is different. Angle of arrival is
calculated from these differing phase measurements using a
specially designed receiver and is delivered to the location
determining system controlling element as azimuth from true north
15 (or other fixed directional reference).

20 The intersection of the rays formed by the reported azimuths
provide the location of the caller. A major advantage of AOA
position finding is that only two sites are required to obtain
a position. Continuous system calibration is also unnecessary.
AOA systems, however, are particularly sensitive to wave
reflections caused by multipath in the urban environment. Their
accuracy degrades also as the distance between the transmitter
(e.g., the handset) and the AOA sensor increases.

25 In TDOA, the difference in the arrival times at multiple
receiver sites of a signal emitted from a transmitter is used to
calculate the position of that transmitter. An advantage of the
TDOA approach is that special antennas are not required - current
site antennas may be used. The sensor typically contains the
functions of reception (filtering, down-conversion), signal
30 sampling and storage, demodulation of certain signals, and
calibration. Continuous calibration or control of system timing
accurate to 10's of nanoseconds is required to achieve the
required time measurement accuracy.

35 A closely related technique to TDOA is TOA, which applies
when the transmitter and receiver are tightly time synchronized.

1 In this case, the differential time alignment in TDOA is not
required, and it is possible to measure the round trip
5 propagation delay between a sensor and a handset, hence infer the
range (distance) to the handset. TOA is normally used in
conjunction with AOA or TDOA to broaden their applicability or
enhance performance.

10 In hybrid angle and time techniques, the location system
attempts to combine the performance advantages of AOA with those
of TOA or TDOA, enabling, in theory, using only one or two
sensors to detect the position of the transmitter (e.g., the
caller's handset), even when poor geometry renders pure AOA
systems ineffective. These hybrid systems also promise improved
15 performance (location accuracy and coverage). The drawback is
the increased complexity at each hybrid site and in system
control.

20 Multipath pattern recognition is an approach which is not
immediately related to TDOA, however it is often combined with
AOA to improve its performance. Multipath pattern recognition
entails comparing the signature of the signal received at various
sensor sites with the that stored in a substantial data base
containing the signatures created during extensive calibration
runs spanning the area. Pattern recognition and classification
algorithms are used to obtain the best match and the location.
25 This technique is better suited to long calls or mobile calls
where a significant amount of filtering can be applied to discard
erroneous matches.

30 In handset based approaches, the handset plays an active
role in performing measurements and optionally computing the
location. Systems pertaining to this family can be divided into
the following three broad classes.

35 Enhanced Observed Time Difference (E-OTD) technique is
essentially TDOA but with the measurements performed at the
handset. The times of arrival of signals from the serving as
well as neighboring cell sites are observed at the handset. This

1 technique also entails the broadcast by the network of the
differences between the actual time bases at the different cell
sites in the area. This information is used by the handset to
5 enhance the location computation if it is performed there.
Alternately, the information on the OTD measurements performed
at the handset could be transmitted back to the network where the
location is computed. In either case, from a location
determination stand point, the technique is similar in its
10 performance to TDOA, but with distinct parameters relating to its
implementation particulars. E-OTD has been the technique of
choice for a number of GSM operators and infrastructure vendors.

Forward Link Triangulation (FLT) technique is essentially
TDOA at the handset. This flavor of TDOA is most commonly
15 applied to CDMA networks because of the tight timing constraints
maintained on the pilot transmitted from each CDMA cell site.
FLT generally uses these pilots from the serving and neighboring
sites to perform a TDOA computation at the handset. Analogous
to E-OTD, some calibration of the time base accuracies at the
20 cell sites is performed and is disseminated over the air to the
handsets.

GPS Based Location techniques rely on the presence of a GPS
receiver or sensor in the handset. Pseudo ranges from GPS
satellites are measured and used to obtain the location. The
25 computation is performed either in the handset or at a server on
the network side if the measurement information is transmitted
back to the network. So called assistance data may also be
transmitted from the network to aid the performance of the GPS
measurements performed in the handset.

30 The tool of the present invention obtains the geographic
coverage and performance of AOA and TDOA based location systems
including their variations and hybrids, whether the measurements
are performed at fixed sensor sites or at the handset. As such,
traditional network-based AOA and TDOA, network-based hybrid
35 AOA/TDOA, and E-OTD and FLT are all techniques whose performance

1 is predicted by the tool. Techniques that apply to a CDMA
network, such as FLT, require special handling in the program to
account for CDMA's unique radio coverage prediction, but as far
5 as location performance prediction, the same procedures and
algorithms described in detail below are applied.

Although the detailed algorithms discussed above do not
explicitly depict the case of GPS measurement in the handset,
because GPS is a TDOA system with the transmitters in the sky,
10 the same methodology described below is readily applied to
predict the performance of those systems as well. Straight-
forward extensions to the propagation, geometry and signal models
used with terrestrial transmitters are applied in obtaining the
performance for the GPS case.

15 FIG. 15 is an exemplary simplified block diagram of some
components included in one embodiment of the tool of the present
invention. As shown in FIG. 15, in this embodiment, the software
tool of the present invention includes the following components:
infrastructure technologies and environment databases 1502,
20 model & algorithm packages 1504, and interfaces 1506. Databases
1502 includes wireless infrastructure databases 1508, location
system deployment databases 1510, geographic databases, and
databases for multipath profiles 1524. geographic databases
include information for: terrain 1518, morphology/land use 1514,
25 roads 1516, salient features 1520 (e.g., large towers or
obstacles), and population 1522.

Model & algorithm packages 1504 include multipath profile
generation/characterization algorithms and multipath profile
databases 1530, location technology databases and location system
30 performance models 1532, propagation algorithm databases 1526,
and reverse link adjustments 1528.

Interfaces 1506 include GUI 1538, printing module &
interface 1540, LAN interface 1542, and outside system interface
1544. System administration utility module 1534 handles the
35 system functions controlled by a system administrator, such as

1 system access control using a password system. System Controller
1536 provide a variety of system control functions.

5 In one embodiment, the software tool supports the entry,
reading, or importing of the specifics of a target cellular or
PCS infrastructure. This wireless infrastructure data includes:
air interface type; cell site locations (latitude and longitude);
site elevation AMSL (maybe computed automatically from terrain);
sector height (above surrounding terrain); number of sectors;
10 antenna gain; TX and RX pattern propagation model type; downtilt;
number of channels; transmit powers; and power control window
upper and lower limits.

15 The default mode of data entry is the keyboard/GUI.
However, other modes of data entry are possible. In one
embodiment, each cell site of an infrastructure is assigned a
number and each of its sectors is assigned another number to
distinguish antennas that may be physically separate (e.g., on
different sides of a building). In one embodiment, the tool
includes separate databases for each target cellular/PCS
20 infrastructure.

25 In one embodiment, the software tool supports entering,
reading, or importing of the location system infrastructure
deployment information. The information pertaining to the
location system deployment includes: location system type or
name; unit type (if multiple receiver types or configurations are
available); location receivers' antenna category (same as
wireless network or not); location system antenna locations
(latitude and longitude or cell site number if same antenna);
antenna type (if not same as cellular); number of antenna units
30 at a given installation; location system antenna elevation;
location system antenna height; and cabling losses. In one
embodiment, the tool includes separate databases for each
location system deployment. Information pertaining to a given
location technology that is not deployment (placement) specific

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1 is maintained in another database called the Location Technologies database.

5 In one embodiment, the tool reads and maintains database with parameters specific to various location technologies. Each databases contains information specific to one location technology or one release version of it that is under investigation. This non-placement specific information is retained in the location infrastructure database. Some of these parameters include: type of technology; antenna types (gains and/or patterns); receivers' sensitivities and noise data; receiver bandwidth; integration time(s); known receiver biases; any known or estimated receiver jitter; quality indicators of receiver or receiver type; and quality indicators computation (if available).

15 The tool contains location system performance algorithm packages to enable predicting system performance. For every location technology identified above, performance computation algorithms are developed using both theoretical and empirical formulas. Distinct modules within each package are possible to compute the effects of specific phenomena on the subject technology, for example, GDOP. The user is able to adjust certain parameters in the equations to support "what if" and sensitivity analyses. These algorithms typically take inputs from multiple databases, including: infrastructure, geographic, multipath profile, and location technology. They also exercise or cause the execution of the propagation package and wireless control algorithms. The outputs of the performance algorithms are expressed in several ways, including: average and RMS errors, probability of missed detection, number and identity of location receivers observing a mobile at given thresholds, and coverage availability (assuming these thresholds). In one embodiment, the results are made available in tabular formats, graphical formats using data layers, and in summary reports.

1 The tool also supports the entry, reading, or importing of
the specifics of mobile units. This data is primarily the unit
type and model. For a number of models, default characteristics
5 are initially read and then maintained into the database. The
characteristics include: peak transmit power; power control
range; support of discontinuous transmission; speech
specification (analog or speech coding rate); and support of data
services, if any.

10 The tool has the ability to read and store the terrain
information for a certain area determined by its corner latitude
and longitude coordinates. The tool is also able to display this
information as a raster data layer. Maps from the USGS or other
private sources conforming to standard formats are supported.
15 For example, both one degree and 7.5 minute arc maps are
supported. 300 m and 100 m terrain maps, among others, are also
supported. The tool also has the ability to read, store and
display morphology type maps. One such source is the USGS Land
Use Land Cover (LULC) data maps. The tool also makes it possible
20 to edit and design custom morphology maps. It displays this
information as a raster data layer.

25 The GUI allows simple entry of many information elements
through dialogue windows. However, some elements may also be
obtainable from sources other than the GUI, e.g., an external
system like a switch or a CD-ROM. Preferably, each database has
a set of menu-driven dialogue windows that enable entering and/or
editing, as appropriate, their information elements. For
example, nominal transmit power, receiver site coordinates,
antenna height, receiver noise figure, land use/morphology
category, and so on. The dialogue windows enable the creation
30 of a new wireless or location site and the entry of its
parameters into the appropriate databases. Preferably, each
model within a package has associated with it a dialogue window
to specify, enter parameter into, or edit (as appropriate) the

1 model. Certain core parts of the models require administrator
access for modification.

5 Prior to performance prediction, two distinct types of site
sectors are defined in a project within the tool: (1) wireless
sectors (e.g., Cellular, PCS, ESMR), and (2) geolocation (or
simply location) sectors. Sites may be comprised of either
wireless sectors, geolocation sectors, or both. A unique
graphical user interface (GUI) allows the user to define the
10 project, enter and edit the particulars of both the wireless and
location sites, and otherwise input and manipulate all the
information that the program may need to provide the predictions
sought by the user. A picture providing an example screen of
this GUI is shown in FIG. 3. An exemplary window within this
15 layered GUI, called the Site Editor, is shown in FIG. 4. The
Site Editor provides a mechanism for the user to input, edit and
select wireless and geolocation site information.

20 Furthermore, the tool is able to read, store and display
interstate, major and secondary roads. This data may be stored
as line or curve rather than raster data. It is possible to
display and/or overlay this information with/on other data
layers. The tool is capable of distinguishing between Interstate
highways and other roads. The tool reads, maintains and displays
population density raster maps. In one embodiment, data based
25 on US census information is used. Also, it is possible to read
or define information elements that specify certain salient
features in the area under investigation. Examples include large
transmitters, tanks, obstructions, airports, etc.

30 The software tool of the present invention begins with
wireless (e.g., cellular) site or area coverage prediction
methods, and adds considerable new modeling to arrive at a
prediction of geolocation network performance. An exemplary
process is illustrated at a top level in the flow charts depicted
in FIG. 1 and FIG. 2. These charts show eight major "boxes" or
35 steps culminating in obtaining the desired location error map.

1 The description below will follow these top level charts and will
elaborate on the eight main steps, providing details on their
algorithmic contents with a more detailed flow chart for each
step.

5 FIGs. 1 and 2 are exemplary process flows according to one
embodiment of the present invention. In block 102 of FIG. 1,
site radial maps for terrain and land use are generated. This
entails developing a radial model and a radial map, centered on
10 the site, for the terrain and morphology (land use) from common
raster maps. The details of this process are shown in the
exemplary flow process of FIG. 5.

15 At each point along a radial path, a combination of
accumulated angular errors and time delay errors (for AOA, TDOA,
their hybrid location techniques) are predicted. The combined
path loss and accumulated error radial maps are then converted
to square raster maps, one for each cellular site and each
geolocation site, as shown in block 104. The details of this
process are shown in the exemplary flow processes of FIGs. 6 and
7.

20 A cluster of sites of fairly arbitrary size is also defined.
The maps calculated for the individual sites are then combined
into a single, combined raster map for the cluster in block 106.
These maps contain at each point, the path loss for the best
wireless server and the error data for the geolocation sites with
25 the highest received signals. Up to N geolocation sites can be
included, where N is currently 8 by default but can be changed.
Details of the steps of block 106 are further described in FIG.
8.

30 In block 108 (explained further in FIG. 9), both forward and
reverse link signal strength maps are computed for the cellular
network to determine the presence of cellular coverage. From
these maps, a map of actual cell phone transmit power is
calculated. The receive power margins are then computed for the

1 geolocation sites (up to N as described above) in block 202
(explained further in FIG. 10).

5 In block 204, a multi-site receive power map, containing the
signal margins at each map point, is then constructed for these
location sites. The additional angle and/or delay noise at each
point due to geolocation sensors receive noise are then
estimated. These errors are combined with the noise previously
10 estimated from the terrain/land use environment and already
available in the cluster raster map in block 206 (explained
further in FIG. 11).

15 In block 208, at each map point, an error covariance matrix
is then generated from the up to N angle and/or time error
estimates. The semi-major axis of the error ellipse is derived
from this matrix, to determine the error estimate, as shown in
block 210 (explained further in FIG. 12).

20 The error results are then output in the form of a display
map covering the cluster or metropolitan area. Color coding is
keyed to the size of the estimated error. Alternately, the
estimated probability that the error will meet a specified
criterion is displayed. The tool is interactive in nature and
allows the user to conduct a number of what-if scenarios, to
optimize location site placement and location system performance.

25 Referring now to FIG. 5, the number of radials required to
adequately represent the site's signal propagation is calculated
in block 502. This number is based on the resolution of the
original terrain file data and the (entered) calculation radius
for the site. The resolution along each radial is typically the
same as the resolution of the terrain file data. Next, the
30 latitude and longitude are calculated in block 512 for each point
(block 508) on each radial (block 504). This requires the sine
and cosine of the azimuth of the radial (block 506 to calculate
the horizontal and vertical distances from the site (center) to
the point on the radial, shown in block 510.

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1 From these distances, the local radius of the earth, and the
site's coordinates, the longitude and latitude of a point on the
radial are determined in block 512. The terrain altitude for the
point (defined by its latitude and longitude) is obtained in
5 block 514 from the original terrain file 516, and a morphology
code is obtained in block 520 from the original morphology files
518. The morphology code is an index into a table that contains
an effective height, loss, and effective obstruction width for
each type of land usage (urban, light suburban, forest, open
10 land, etc.). This information is then stored together in radial
format. This process is repeated for the next point (blocks 522
and 524) and the next radial (blocks 526 and 528).

15 The second major step for the top level exemplary process
flow of FIG. 1 is to generate the radial files for path loss and
for the time and/or angle error, as shown in block 104. In one
embodiment, the tool includes a set of propagation models that
can be selected by the user for the purpose of computing the path
loss. The selection may be based on a sector, or larger areas.
20 The following models are some examples of the propagation model
selections: Okumura-Hata (cellular band), Cost 231 (PCS band),
Line of Site, Lee's model with effective antenna height, Fresnel
zone corrections for paths partially obstructed by terrain.
Other propagation models may be easily added to the tool. The
25 user has the ability to override key default parameter values in
the model selected.; for example, the intercept of the Hata
model (as seen on a log-log scale).

30 Furthermore, the design of the propagation module enables
importing measurement data in a standard file format to perform
least square fit type computations. The results of these
computations are used to adjust the parameters of the selected
propagation model over a certain application region to be defined
by the user. Another capability of the tool is to automatically
select a permissible combination of models (e.g., O-H and LOS)
35 on a per-pixel, per site basis. For each propagation model made

1 available on the forward wireless link, a set of adjustments are
implemented to allow its use for predicting the reverse link path
loss. The details of this multi-faceted process are depicted in
5 the exemplary process flow of FIG. 6.

Referring now to FIG. 6, several salient sub-steps are shown
including: spherical (4/3) earth computation (block 606);
propagation model computation to generate the path loss including
the effects of diffraction and antenna height (blocks 628 and
10 630); computation of loss due to antenna pattern (block 638);
computation of the angle errors (block 662) or time errors (block
660) that result along the radial paths in an AOA or TDOA based
system, respectively.

For each entry along each radial route, the total number of
15 obstructions is determined and the characteristics of each path
leg from site to obstruction to other obstruction(s) to mobile
unit are determined in block 620, and the accumulated diffraction
loss is calculated for each obstruction in block 628.
Diffraction loss is calculated similar to the method described
in "The Mobile Radio Propagation Channel, Parsons, Halsted Press,
20 1992, pp 48-49," the contents of which are expressly incorporated
by reference herein, following the "The Epstein-Peterson method".

For each point (block 616), the number of path legs are
obtained in block 620. For each path leg (block 626), the
25 diffraction loss is calculated and summed, as shown in block 628.
From the last path leg, and the average slope of the land just
before the mobile unit, the effective height of the site antenna
is calculated in block 630. Both the ray from the mobile and the
slope of the land just before the mobile are projected back along
30 the last leg to the site antenna position and the difference in
altitude is used as the effective antenna height. From this and
the total distance to the mobile unit, the nominal path loss is
determined in block 632 from a selected propagation model 634
(e.g. Hata, Cost 231).

1 A host of standard propagation models are made available to
the user to predict the path loss along each radial. Hybrid
variations of these models are also permissible in the tool.
5 For example, Okumura-Hata (O-H) is one typical model widely used
for urban or suburban propagation. The O-H model includes
parameters that could be adjusted and selected by an expert user
to adapt it specifically to certain propagation environments,
e.g., an unusually open area. The tool's user friendly GUI
10 permits the user to select and edit these detailed parameters of
the propagation model. Other models that are more appropriate
for specialized propagation environments, e.g., for very high
sites, can be used, at the user's option, instead of a standard
O-H model.

15 This propagation model is then modified by the morphology
loss at all points where the ray penetrates the morphology.
Using the azimuth of the current radial and the elevation to
mobile unit or first obstruction, if any; the stored antenna
pattern 636; and the antenna's azimuth and tilt, the antenna
20 pattern loss is determined in block 638. This loss is added for
the total modeled path loss in block 640.

25 At each point along a radial path (blocks 644 and 646), a
combination of accumulated angular errors or time delay errors
are computed as applicable (for AOA, TDOA, and hybrid location
techniques). The angular measurement error is accumulated along
the propagation path below the morphology (clutter) height based
on an equivalent obstruction size, an equivalent obstruction
density, and the distance from the sensor antenna. The steps in
blocks 648 and 650 are used to determine whether or not each of
30 the rays is impacted by the clutter. The type of the algorithm
to be used for the analysis is determined in blocks 652 and 654.

35 In block 656, individual AOA errors are calculated by
calculating the angular error from the antenna caused by the path
diffracting around the obstruction (or reflecting off an adjacent
obstruction). In block 658, TDOA errors are calculated by

1 subtracting the direct path from the site from the path around
the obstruction to the mobile unit. Each error is squared for
accumulation as a variance in blocks 660 for TDOA/EOTD and block
5 662 for AOA.

The equivalent obstruction sizes and densities are abstract
terms arrived at through integrating field measurements into the
model and are different for each morphology (land use) type. The
resolution along the radial path remains consistent with the
10 terrain/morphology database. Next point and next leg is selected
in blocks 664 and 668, respectively. If the end of loop is not
reached (block 676), next point is selected in block 616. If the
end of loop is reached, next radial is selected for analysis in
block 610.

15 The next major step in FIG. 1 is to convert the combined
path loss and accumulated error radial maps to square raster
maps, one for each cellular site and each geolocation site. In
one embodiment, the details of these conversions are performed
as shown in FIG. 7. In FIG. 7, first, the box map dimensions are
20 determined to fit the radial signal file and the box map is set
to the same resolution as the radial distance resolution, as
shown in block 702. From here, a signal map entry is obtained
(block 708) for each latitude and longitude (blocks 704 and 706)
in the box map. The signal data (path loss and error) is then
25 stored in the box map's raster format, as shown in block 712.

It is quite common for radio engineering and location system
planners to focus their analysis on a subset of the sites that
have been initially entered into the project prior to processing.
This is, for example, to examine in more detail a specific area
30 or section of a city, or to conduct what-if analyses. The
cluster size is fairly arbitrary. The rectangular maps
calculated in the previous step for the individual sites are now
combined into a single, combined raster map for the cluster.
The details of this procedure are depicted in the exemplary
35 process flow of FIG. 8. The cluster maps contain at each point

1 the path loss for up to N sites as their coverage usually overlaps.

5 Referring to FIG. 8, based on the user's input, the boundaries (latitude and longitude) of the overall cluster are determined from the site box map 805 sizes and positions, as shown in block 802. Then, the box map is aligned with the cluster map in box loop of block 804. This is done by obtaining the box map's upper left coordinate (latitude and longitude) in
10 block 806 and determining where this position is in the Cluster map, as shown in block 808. Inserting the box data into the cluster map starts at this point. At each point in the cluster map (blocks 820 and 822), the signal is extracted from the box map 805 in block 824 and is inserted into the cluster map in block 828. In this process, the site signals are ordered by
15 received signal strength, the best wireless server being first in the list. These are the sites with the highest signal levels received from the handset (or vice-versa at the handset). The default value for the number of sites N is 8, but can be changed and selected differently by a user. The resolution of the
20 cluster maps is user selectable but is typically the same as the original terrain maps.

Referring back to the high level exemplary process flow of FIG. 1, the next step is computing the forward and reverse link
25 signal strength maps for the best server in the cellular network, as shown in block 108. This is to determine the presence of cellular coverage. (This implies that the tool also determines the likely/best server for a given mobile's location.)

As shown in FIG. 9, for each line in the cluster map (block
30 902) a signal strength is obtained. The path loss is subtracted from the effective radiated power (ERP) of the best server site to obtain the forward signal strength. Alternatively, the path loss is subtracted from the maximum ERP of the mobile unit to obtain the reverse signal strength, as shown in block 912. The
35 ERP of the cellular sites are obtained from the Site Data

1 database 908 and the maximum ERP of the mobile unit from the
mobile unit data database 910.

5 Full use of most of the propagation models for path loss
computation requires the availability of terrain information.
Nevertheless, In one embodiment, the tool has two modes: a no
terrain mode and a full terrain mode. When no terrain
information is available the user enters a height for the mobile
manually. The overall heights of the cell sites is computed from
10 manual input of site elevation AMSL plus manual input of an
antenna height. When terrain data is available and accessible,
the tool automatically computes the site and mobile user
elevation from the coordinates manually provided and the antenna
height entered.

15 From the forward and reverse link signal maps (block 108),
a map of actual cell phone transmit power is calculated in block
202. The details of this steps are shown in FIG. 10. For each
cluster line (block 1010) and cluster column (block 1012),
forward signal margins and return signal margins are calculated
in blocks 1024 and 1028, respectively. From the forward signal
map 1014 and mobile unit data 1016, path loss and mobile unit
receive sensitivity is subtracted from the ERP of the best server
site to obtain forward signal margin, as shown in block 1024.
20 If this margin is positive (block 1026), from return signal map
1018 and site data 1020, path loss and site receive sensitivity
is subtracted from the ERP of the mobile unit to obtain the
return signal margin, as shown in block 1028.

25 In block 1030, the mobile unit power is calculated as the
minimum power necessary to maintain the reverse link so long as
both the forward and reverse margins are positive. Mobile unit
power never goes below the minimum mobile unit power entered into
the program. The computation takes into account the power
control implemented in the wireless network and followed by the
handset. Again, the particular parameters of the mobile unit are
30 obtained from the mobile unit data database 1022.

1 As depicted in block 204 of FIG. 2, the receiver powers are
now computed. The receiver power margins are also computed as
described in the previous paragraph for the pertinent geolocation
5 sites (up to N as described above). As shown in block 206, a
multi-site margin/error map, containing the signal margins at
each map point, is then constructed for the N location sites.
This map is essentially identical to the cluster map discussed
previously, except that the location sensor sites are used
10 instead of the cell sites and the error data is recorded in
addition to the signal margin data. Using algorithm database 126
the propagation algorithms 128, and the time/angle error
algorithms 130, a computation is performed at this stage to
include the additional angle and/or delay noise at each point due
15 to geolocation sensors receive noise. These are based on sensor
characteristics and signal margins. The details for these
algorithmic steps are shown in FIG. 11.

Similar to the exemplary process of FIG. 8, the boundaries
(latitude and longitude) of the overall cluster are determined
20 from the site box map sizes and positions using the location
signal box maps 1104, as shown in block 1102 of FIG. 11. Then,
the box maps within the overall cluster map are aligned with it.
This is done by obtaining the box map's upper left coordinate
(latitude and longitude) in blocks 1110 and 1114. Next, for each
25 location in each box map (block 1126 and 1128), latitude and
longitude are determined in block 1130. The latitude and
longitude are then converted to the line/column coordinates used
in the mobile unit power map, as shown in block 1132. The mobile
unit power is then obtained in block 1133, similar to the process
30 of FIG. 10.

Depending on whether the mobile unit is transmitting
(because it has positive cellular link margins), then the signal
margin to the location sensor (forward or reverse) is determined
in blocks 1158 or 1154, respectively. If the margin is positive,
35 then the appropriate error is added to the position by insertion

sort in blocks 1168 or 1166 depending on the type of the location algorithm used (blocks 1162 and 1164). These location sensor related errors are combined with the errors previously estimated from the terrain/land use environment and already available in the cluster raster map.

The final computational step in FIG. 2 is to obtain at each map point an error covariance matrix from up to N angle and/or time error estimates, as shown in block 208. The semi-major axis of the error ellipse is derived from this matrix. This is the error estimate at any given point on the map. The detail of this step is shown in exemplary process flow of FIG. 12.

Referring now to FIG 12, for each line and each column (blocks 1202 and 1204), using the Multi-site Error map 1210, the inverse of the covariance matrix is calculated in block 1208. The inverted matrix 1212 is then used to calculate the semi-major axis of the error ellipse in block 1214.

The covariance matrix for AOA is:

$$\mathbf{P} = \begin{bmatrix} \sum \left(\frac{-\Delta y_k}{d_k * v_k} \right)^2 & \sum \left(\frac{-\Delta y_k}{d_k * v_k} \right) * \left(\frac{\Delta x_k}{d_k * v_k} \right) \\ \sum \left(\frac{-\Delta y_k}{d_k * v_k} \right) * \left(\frac{\Delta x_k}{d_k * v_k} \right) & \sum \left(\frac{\Delta x_k}{d_k * v_k} \right)^2 \end{bmatrix}^{-1} = \begin{bmatrix} \sigma_x^2 & p_{12} \\ p_{21} & \sigma_y^2 \end{bmatrix}$$

where: Δy_k = vertical component of distance from position to site k.

Δx_k = horizontal component of distance from position to site k.

d_k = distance to site k.

v_k = variance of measurement k.

For TDOA, the covariance matrix is:

$$\mathbf{P} = \begin{bmatrix} \sum \left(\frac{\Delta x_k}{d_k * v_k} \right)^2 & \sum \left(\frac{\Delta y_k}{d_k * v_k} \right) * \left(\frac{\Delta x_k}{d_k * v_k} \right) & \sum \left(\frac{\Delta x_k}{d_k * v_k} \right) \\ \sum \left(\frac{\Delta y_k}{d_k * v_k} \right) * \left(\frac{\Delta x_k}{d_k * v_k} \right) & \sum \left(\frac{\Delta y_k}{d_k * v_k} \right)^2 & \sum \left(\frac{\Delta y_k}{d_k * v_k} \right) \\ \sum \left(\frac{\Delta x_k}{d_k * v_k} \right) & \sum \left(\frac{\Delta y_k}{d_k * v_k} \right) & \sum \left(\frac{1}{v_k} \right) \end{bmatrix}^{-1} = \begin{bmatrix} \sigma_x^2 & p_{12} & p_{13} \\ p_{21} & \sigma_y^2 & p_{23} \\ p_{31} & p_{32} & \sigma_b^2 \end{bmatrix}$$

where: Δy_k = vertical component of distance from position to site k.

Δx_k = horizontal component of distance from position to site k.

d_k = distance to site k.

v_k = variance of measurement k.

For combined AOA-TDOA, the first matrix is added to the upper left rows and columns of the second matrix and then the resulting matrix is inverted to yield the desired covariance matrix.

In all three cases, the semi-major axis of the error ellipse is:

$$\sigma = \sqrt{\frac{1}{2} \left[\sigma_x^2 + \sigma_y^2 + \sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4P_{12}^2} \right]}$$

The error results are then output in the form of a display map covering the cluster or metropolitan area. Color-coding is keyed to the size of the estimated error. An example of this output is shown in FIG. 13. Alternately, the estimated probability that the error will meet a specified criterion is displayed. A host of intermediate results such as forward and reverse link margins and Cellular best server can also be

1 displayed in support of location system planning activities.
Another very useful output plot is the number of location sensors
"seeing"; i.e., receiving a useful signal above sensitivity
5 floor, from a handset. An example of this type of plot is shown
in FIG. 14. Outputs as those shown in FIG. 13 and FIG. 14
provide clear graphical representations of location system
accuracy and availability.

10 Default outputs in many cases are graphical; e.g., location
error contours, GDOP contours, coverage areas, color coded
regions to indicate the number of observing receivers above a
certain threshold., and so on. However, the user has the option
to display certain outputs in other formats, e.g., tables.

15 Printing dialogue windows are user friendly, permitting the
user to use both map scale specifications as well as mouse
movements to select the printable area. Different icons are used
to signify different site categories. For example, existing,
proposed, what-if, and neighboring are possible categories that
have somewhat different icons to assist the user in the analysis.

20 The user is able to select the colors for the color-coded
displayed categories through dialogue windows under an "Options"
menu entry. Preferably, certain color components, e.g., terrain
shading gradations, water bodies, morphology categories,
highways, etc., may be available for selection by the user. The
25 graphical outputs are of sufficiently high resolution and the
refresh speed of the screen is maintained high enough to provide
the user with a good work environment.

30 Moreover, the tool supports common business-quality inkjet
color printers. Varying paper sizes are supported by the tool
as well. Black and white report and table printing are also
supported. In one embodiment, printing control is performed
through menu selection. Printer selection and feature control
are provided through printer setup dialogue windows. Print item
or area selection are provided through dialogue windows. Both
35 keyboard entry of print object size as well as mouse-based

1 specification of an area on the display are possible. Both
direct connection to the printer and connection through networks
such as a LAN are supported.

5 The tool also supports interfacing to certain outside
systems. It is convenient at times to import database
information from outside sources. This, at times, is the only
way a database can be maintained current with a dynamic
deployment. For example, the cell site database may be
10 maintained in the mobile switching center (MSC) or connected to
it and has up to date information on the wireless systems' cells,
channel assignments, powers, etc. This information may also be
imported by the tool.

15 The tool also provides data base and system security.
Preferably, user created data used in an analysis session cannot
be deleted except by its owner or by the system administrator.
Also, a user may save the data used in a session for subsequent
use. The system includes password access control for using the
tool.

20 With its user friendly GUI, structured menus, and various
intermediate and final output options, the tool is a flexible,
interactive tool that offers the wireless location system planner
a host of powerful design capabilities. Not only does it enable
the user to determine location system performance, it also
25 enables him or her to conduct exercises to optimize location site
placement, and to perform various coverage and cost-benefit
tradeoffs.

30 It will be recognized by those skilled in the art that
various modifications may be made to the illustrated and other
embodiments of the invention described above, without departing
from the broad inventive scope thereof. It will be understood
therefore that the invention is not limited to the particular
embodiments or arrangements disclosed, but is rather intended to
cover any changes, adaptations or modifications which are within
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the scope and spirit of the invention as defined by the appended
claims.

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